The annual cycle of circulation in the southwest subtropical Pacific

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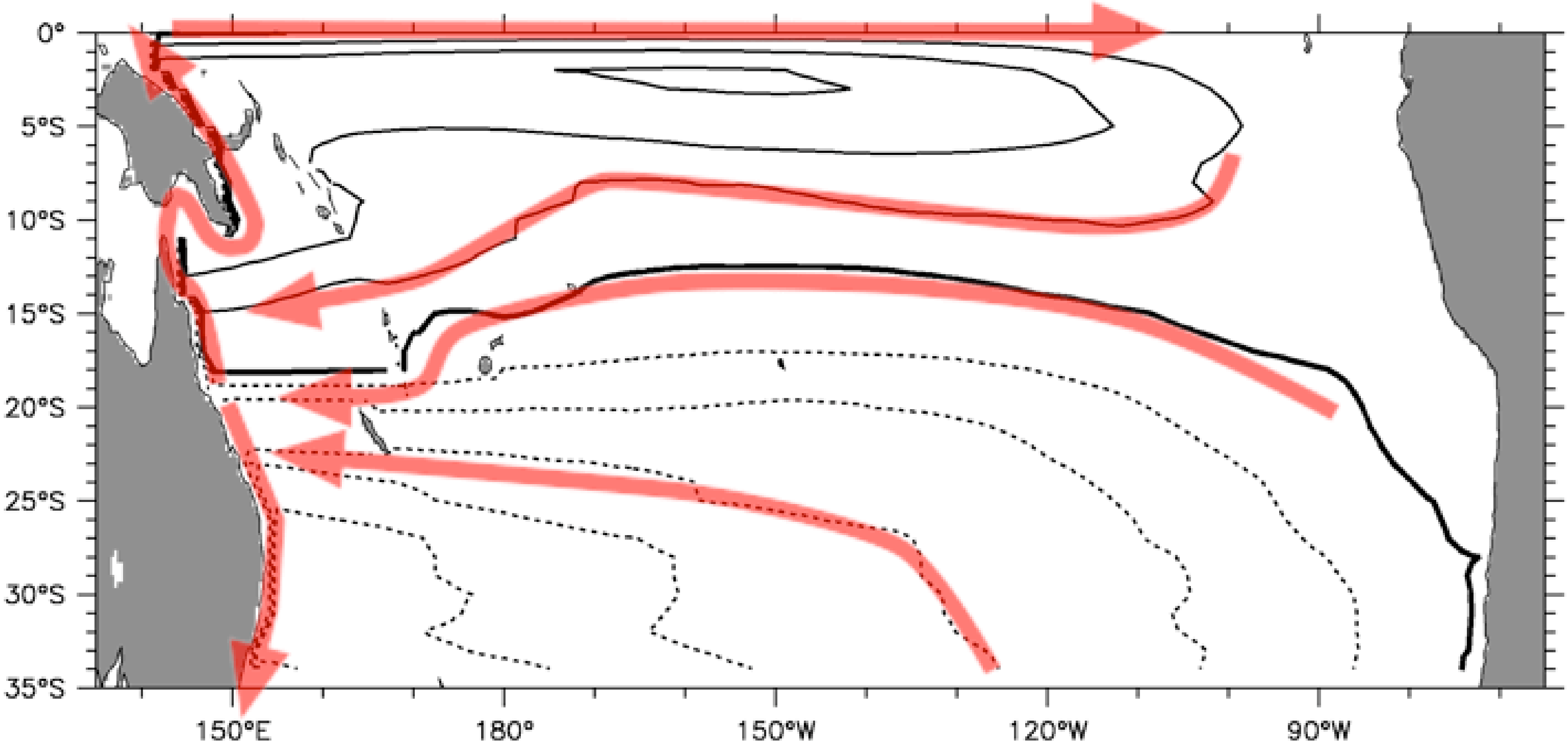
- We are interested in the southwestern Pacific because of its position athwart a major pathway from the subtropics to the equator:
  How are water masses redistributed at the western boundary?

- It is likely that interannual and decadal variability is most climatically important, but here we take a first step by looking at the annual cycle.

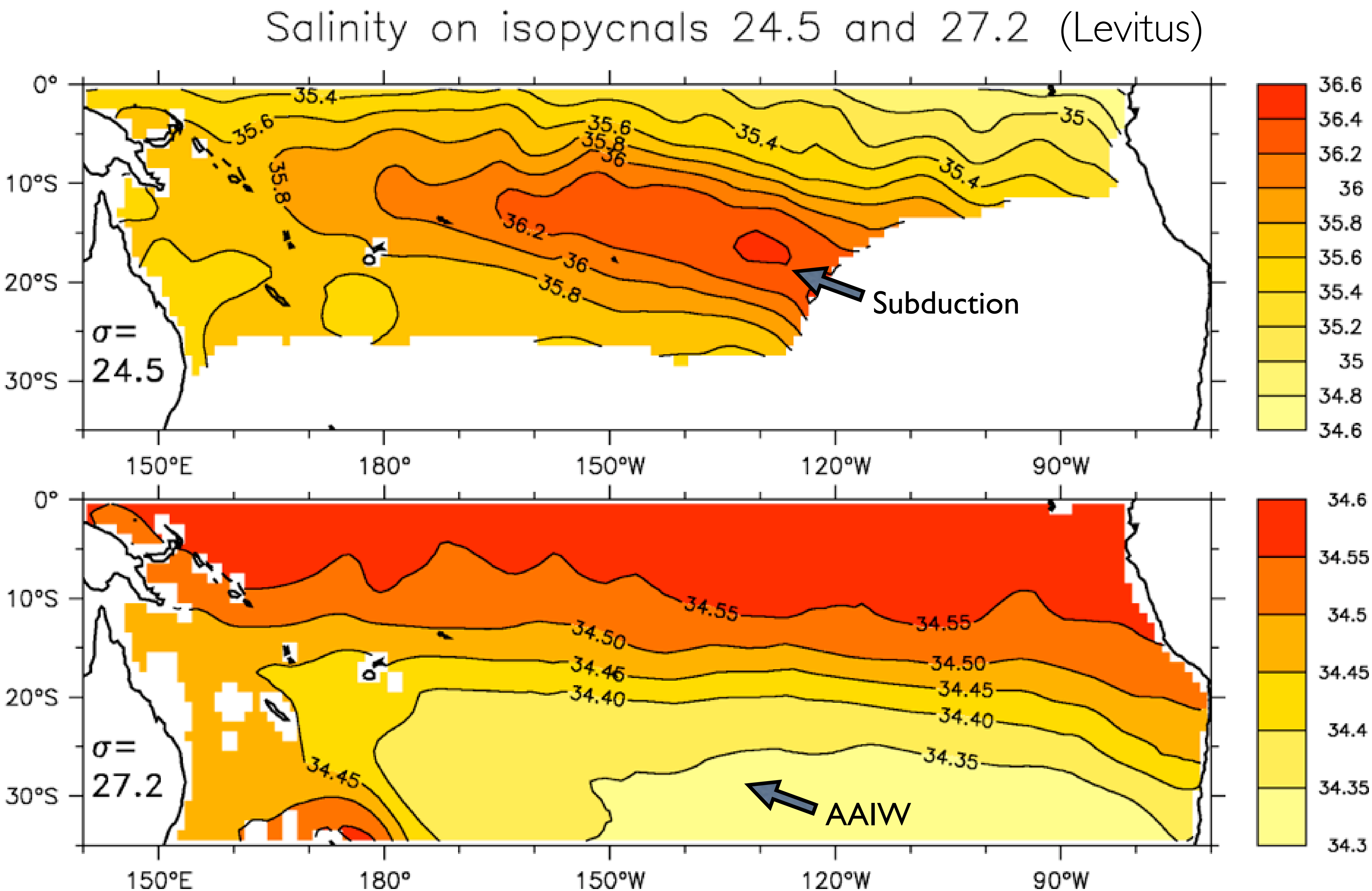
- In the absence of observations sufficient to diagnose the variability, we analyze an ocean GCM (OPA/ORCA).

The big picture: Redistribution of mass at the western boundary

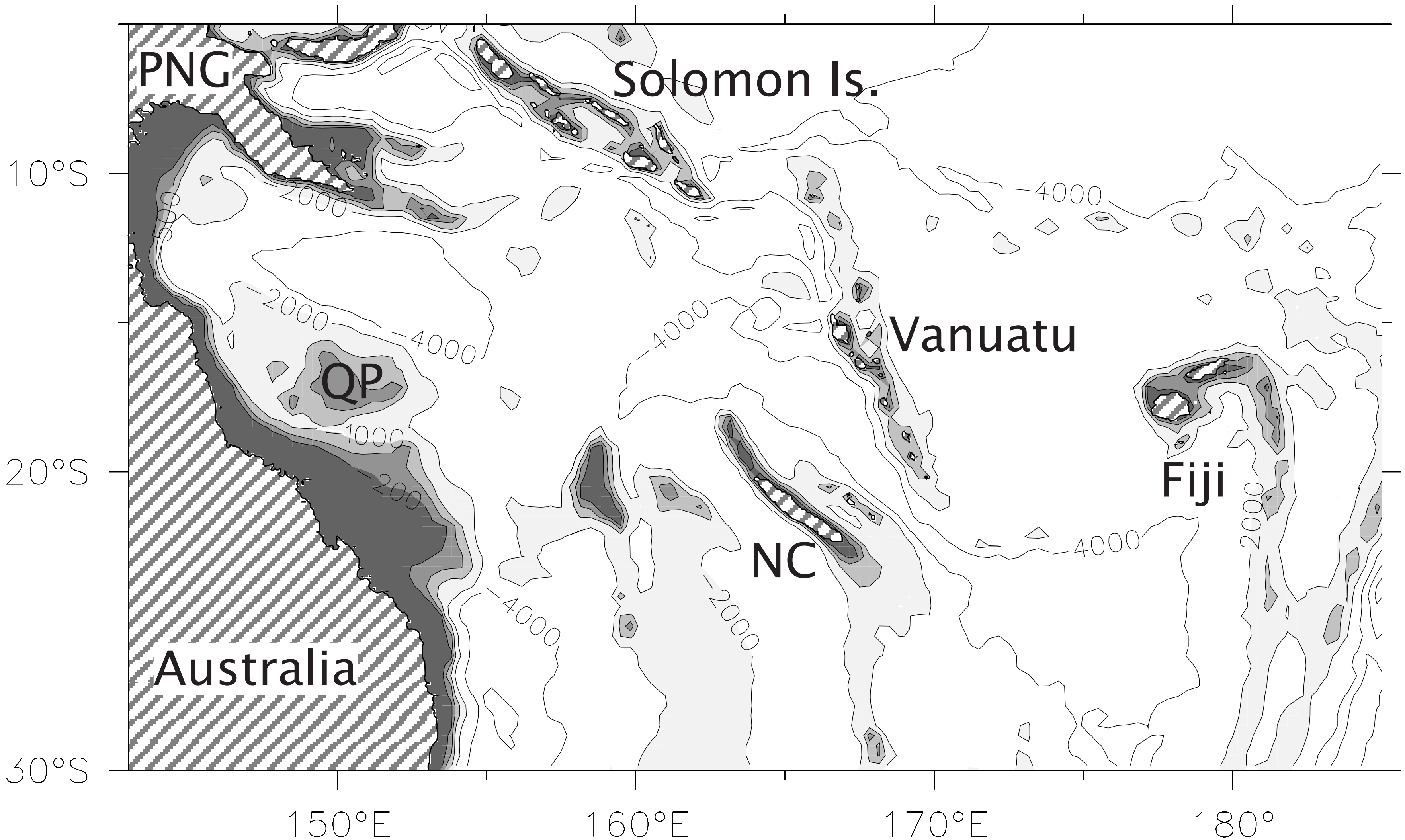
Island Rule (Sverdrup) streamfunction (ERS winds)



Water mass redistribution in the SW subtropical Pacific

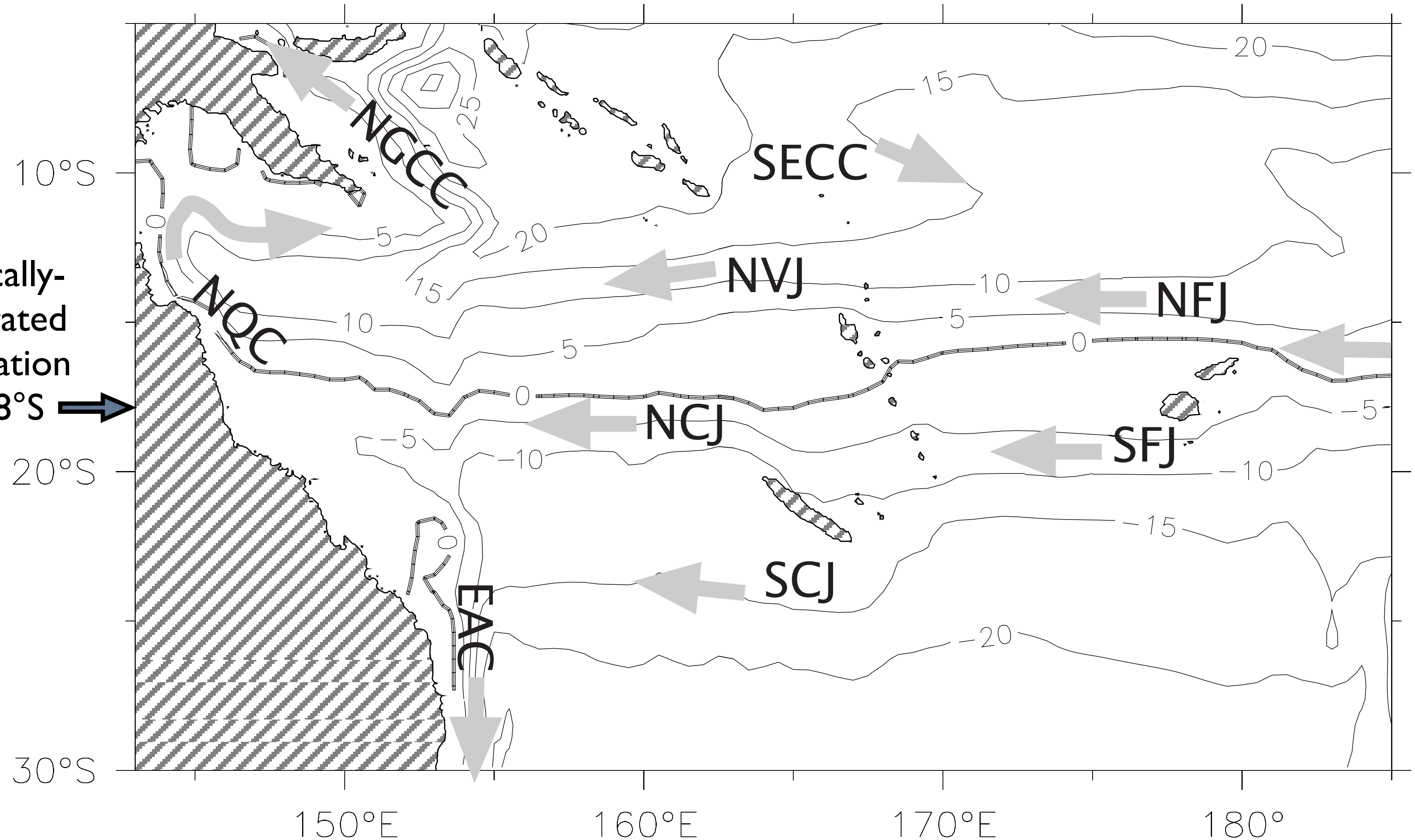


Bathymetry of the SW Pacific



ORCA model streamfunction

Vertically-integrated bifurcation at 18°S



Western Boundary Currents

EAC = East Australian Current

NQC = North Queensland Current

NGCC = New Guinea Coastal Current

SECC = South Equatorial Countercurrent

N, SFJ = North, South Fiji Jet

NVJ = North Vanuatu Jet

N, SCJ = North, South Caledonian Jet

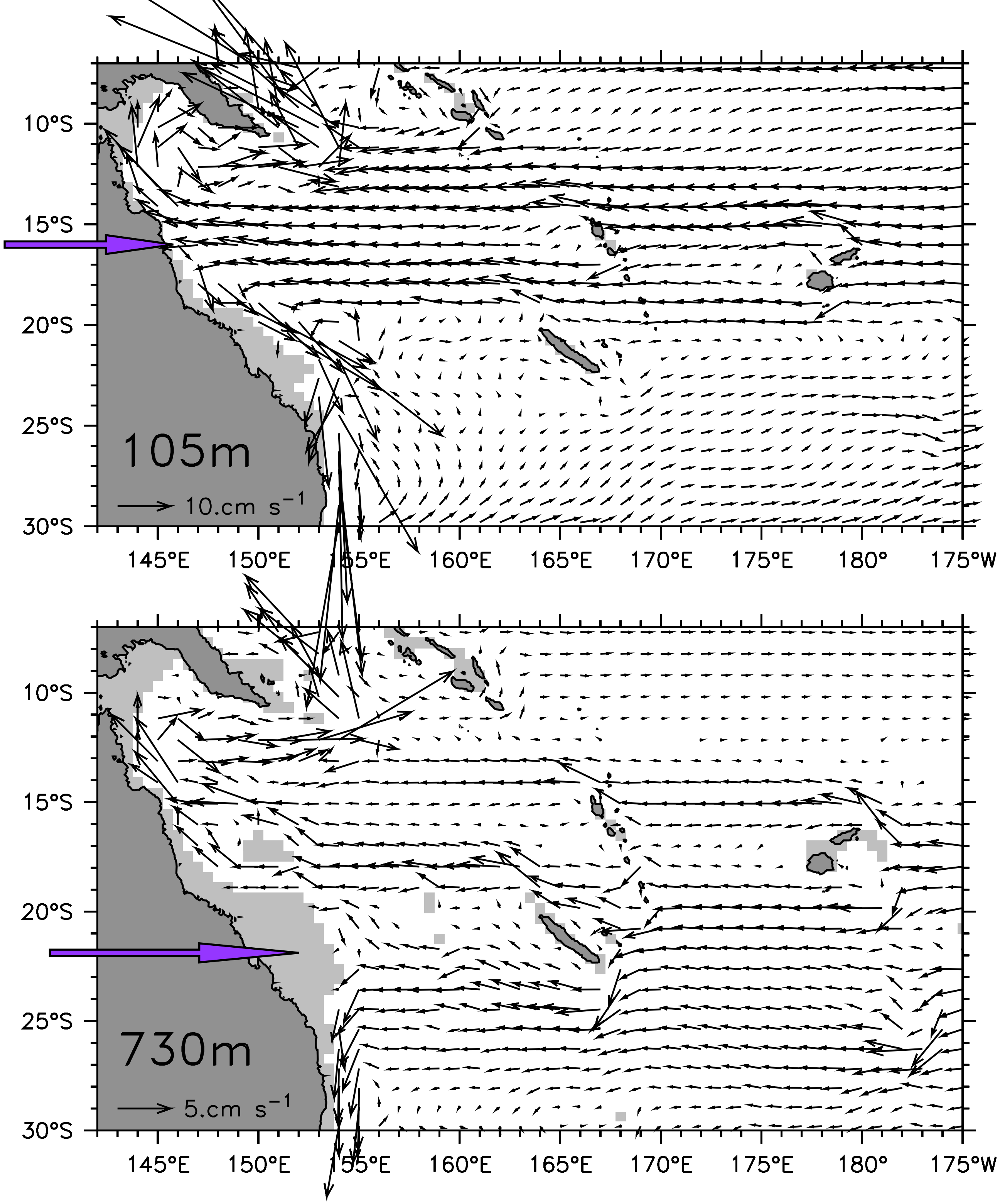
Tilted gyre, tilted bifurcation

105m

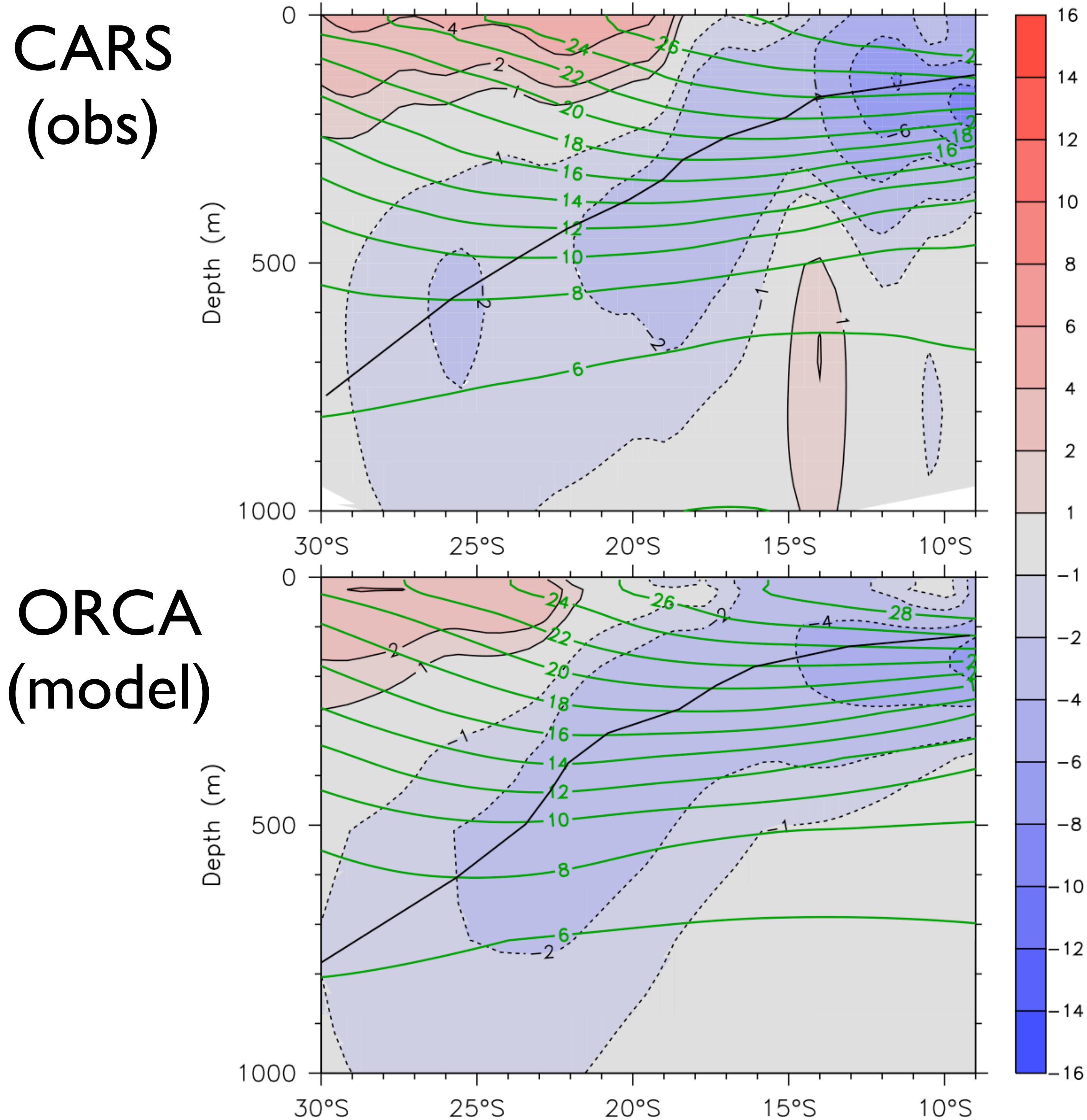
Bifurcation at 16°S

730m

Bifurcation at 22°S



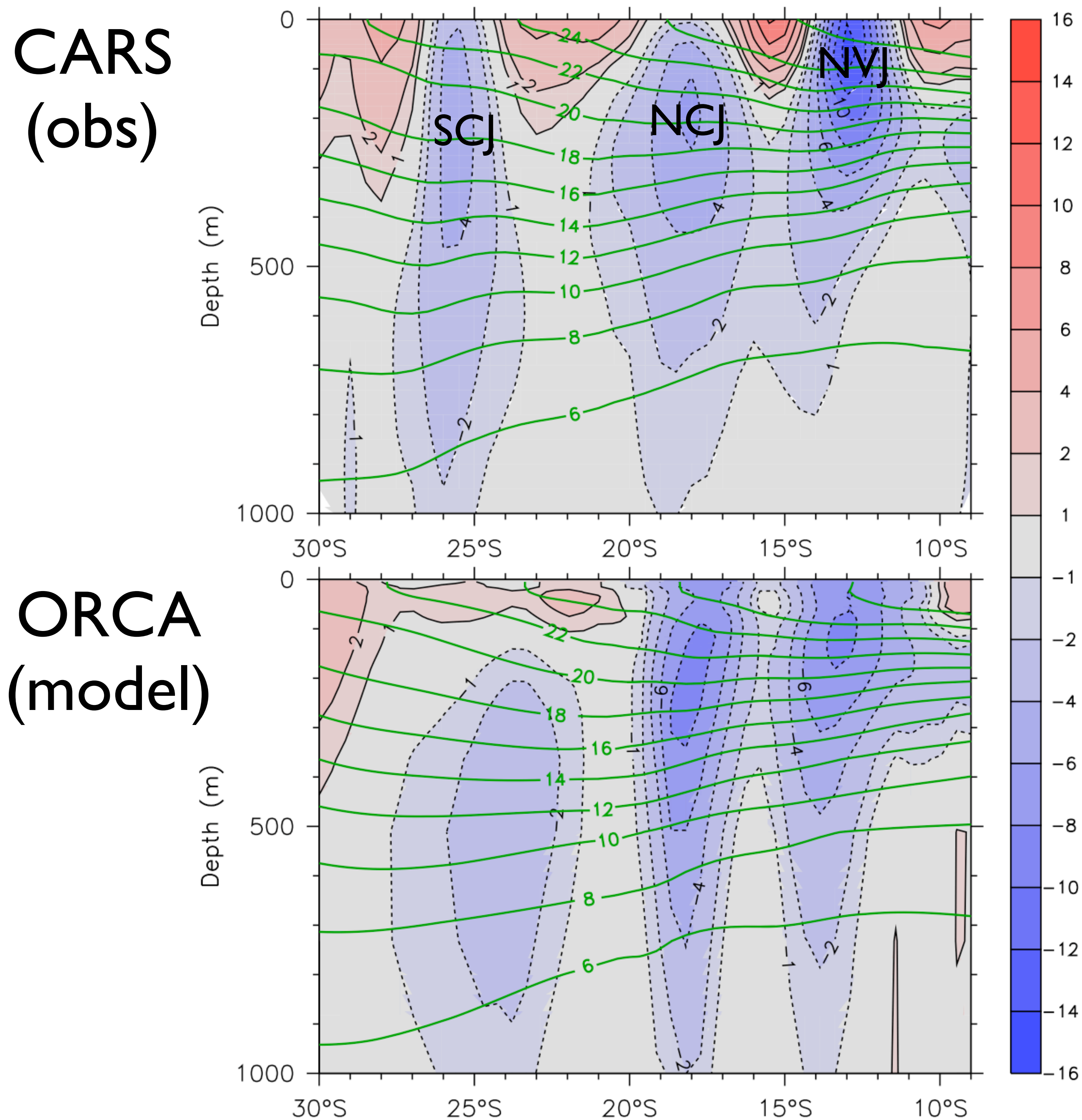
Zonal current and temperature at 175°W



CARS is a new CSIRO CTD compilation for the S Pacific and S Indian Oceans

Ridgway & Dunn (2003)

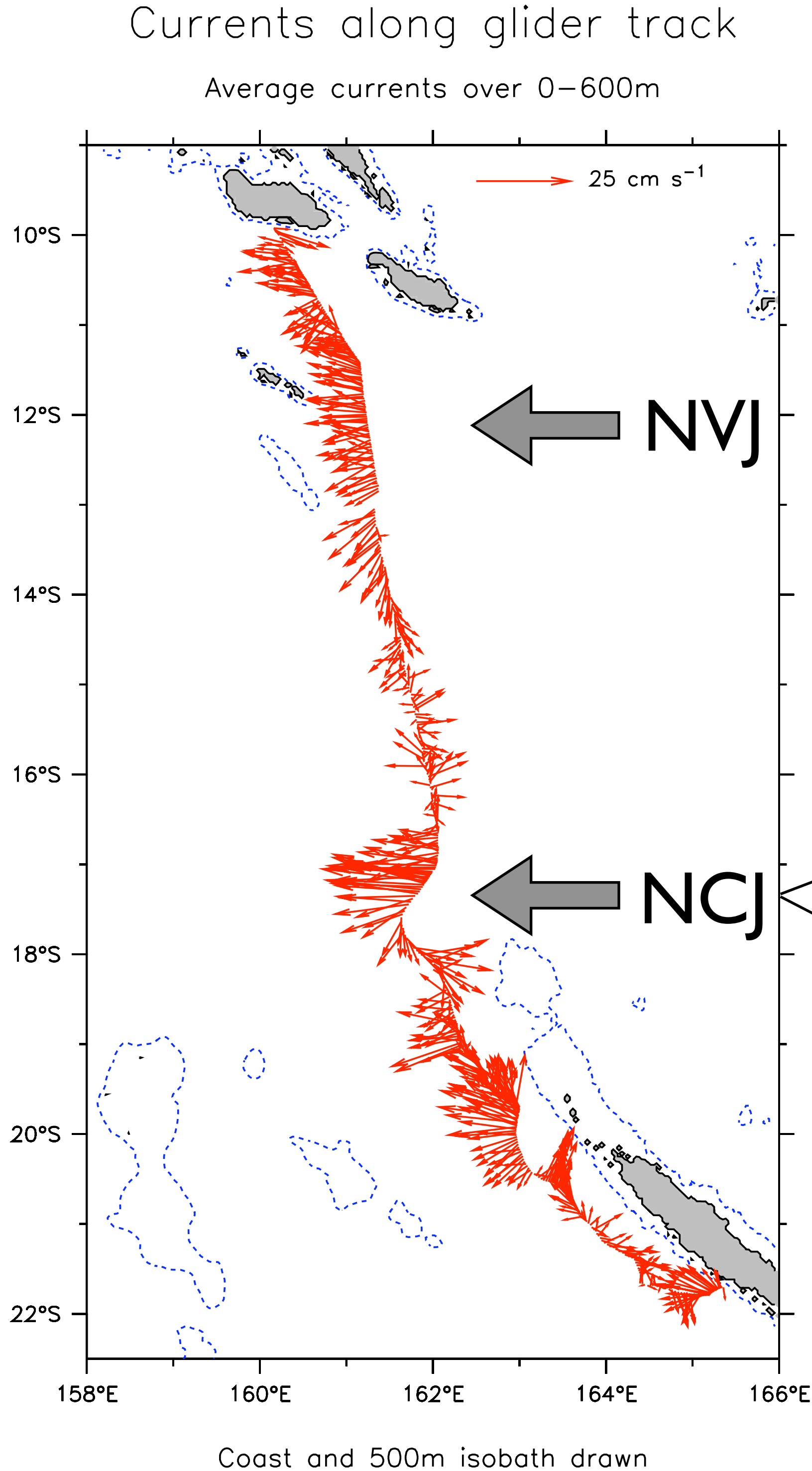
Zonal current and temperature at 162.5°E

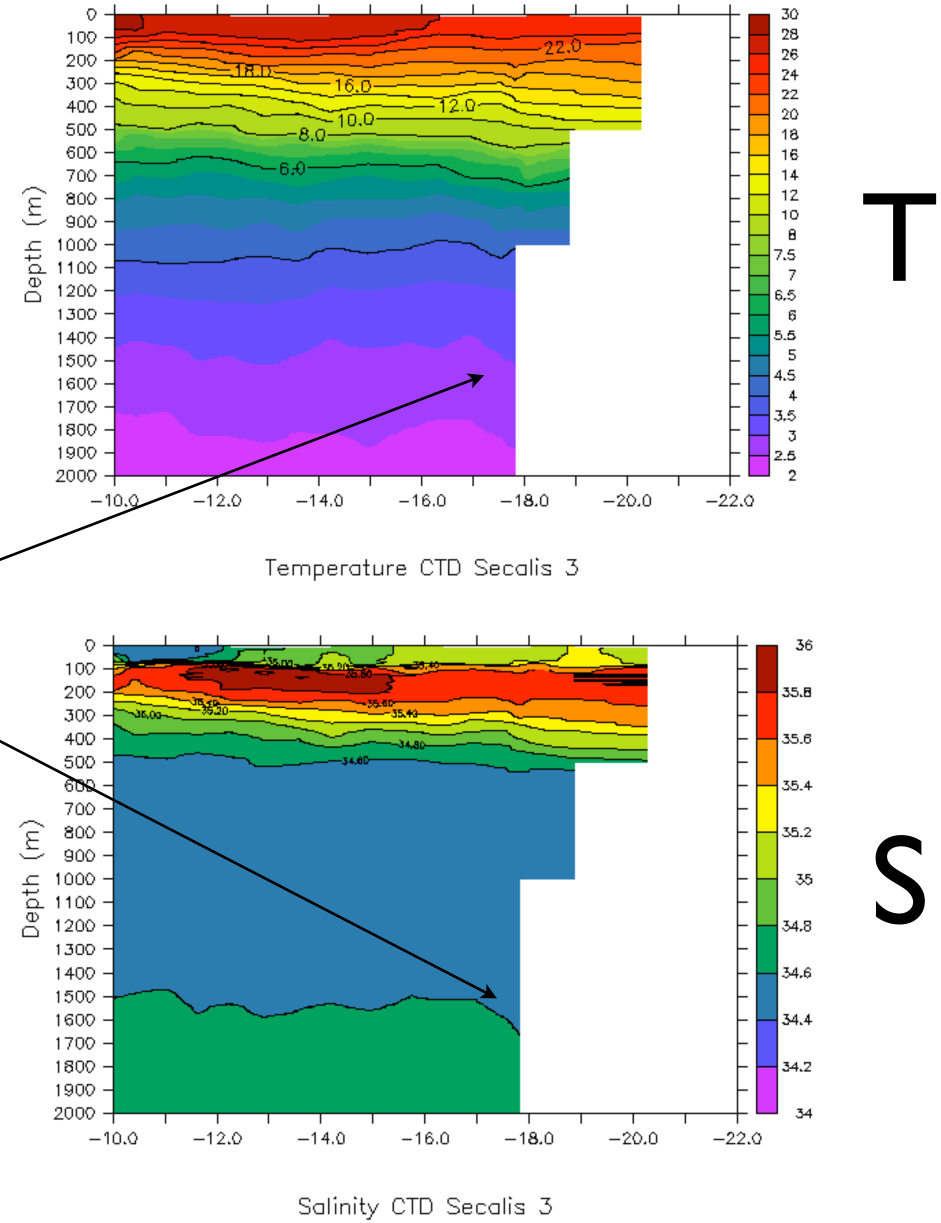


The SEC is broken into distinct jets behind the islands.

The jets have subsurface maxima.

The NCJ extends very deep!
Sections during July-Oct 2005

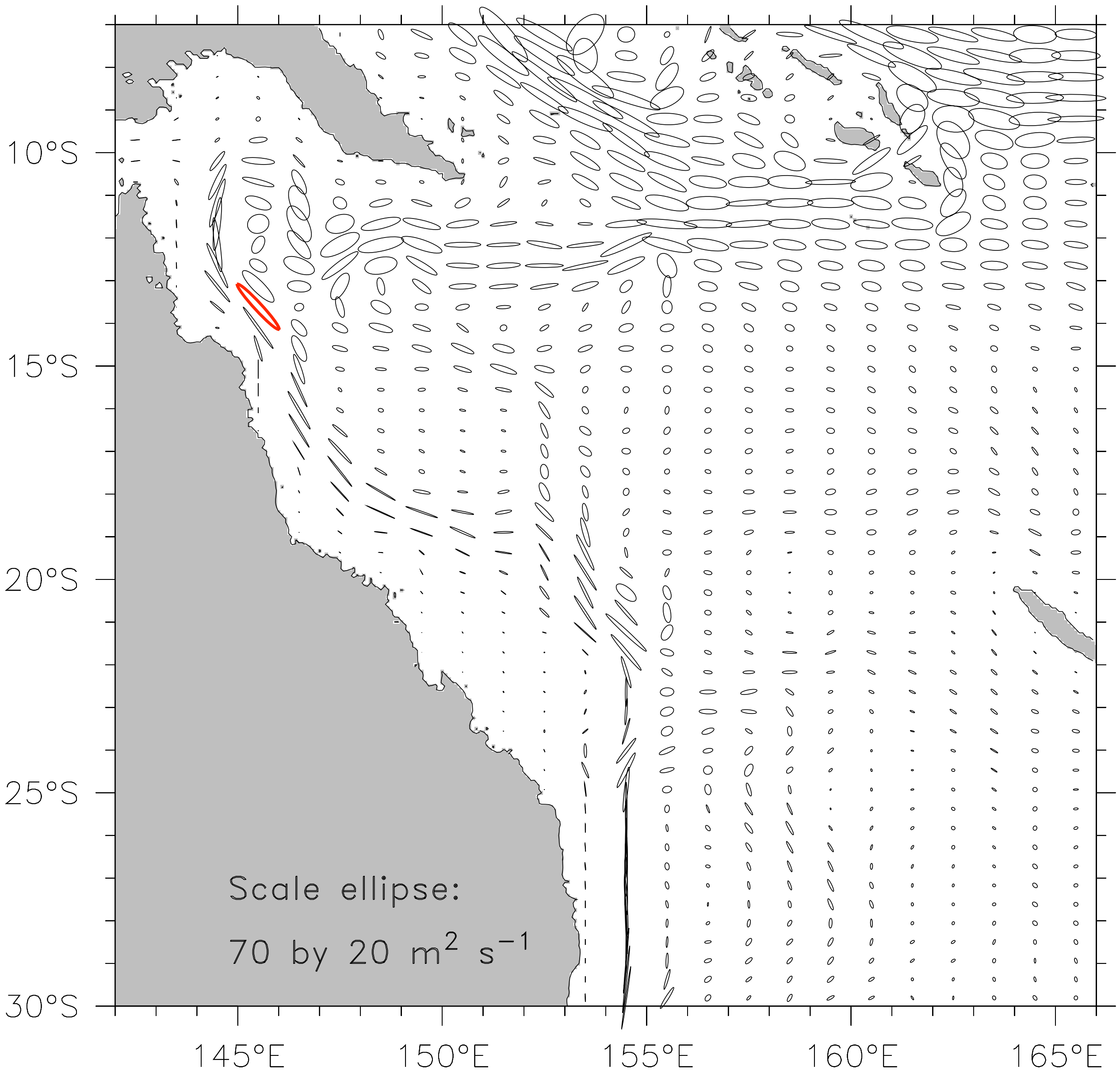




Summary of brief look at mean circulation

- Complex regional geometry/topography
- SEC divided into jets
- Tilted gyre (hence tilted bifurcation)
- Bifurcation/redistribution of SEC inflow
  - ⇨ Climate consequences?
  - ⇨ Implication that variations of the bifurcation produce transport anomalies to the equator

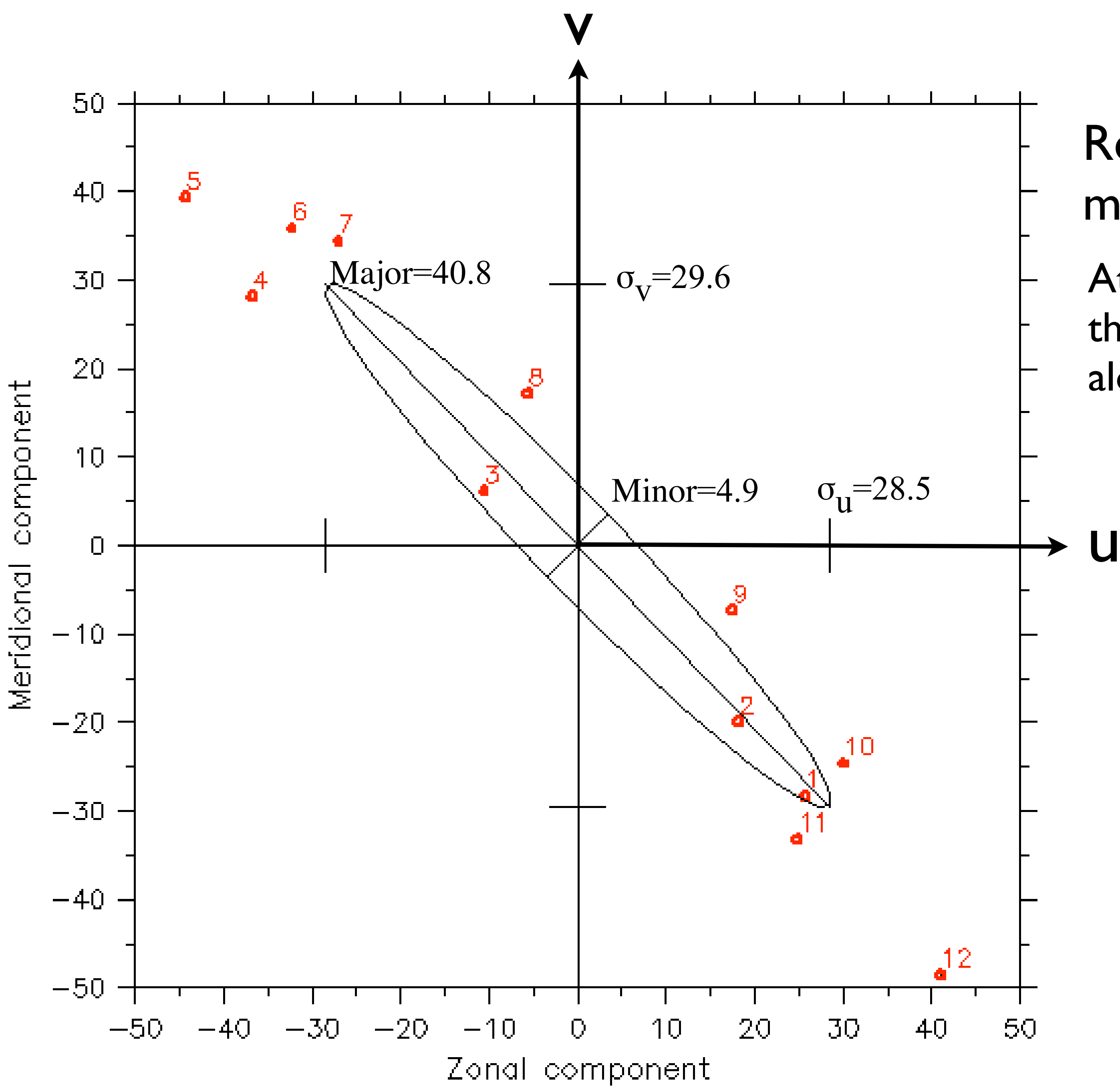
Annual cycle transport variance ellipses



0-2060m transport

The major and minor axes of a variance ellipse are the standard deviations of the velocity components, *after the ellipse has been rotated to express the maximum possible variance in the major axis direction.*

Variance ellipse at 13.6°S, 145.5°E

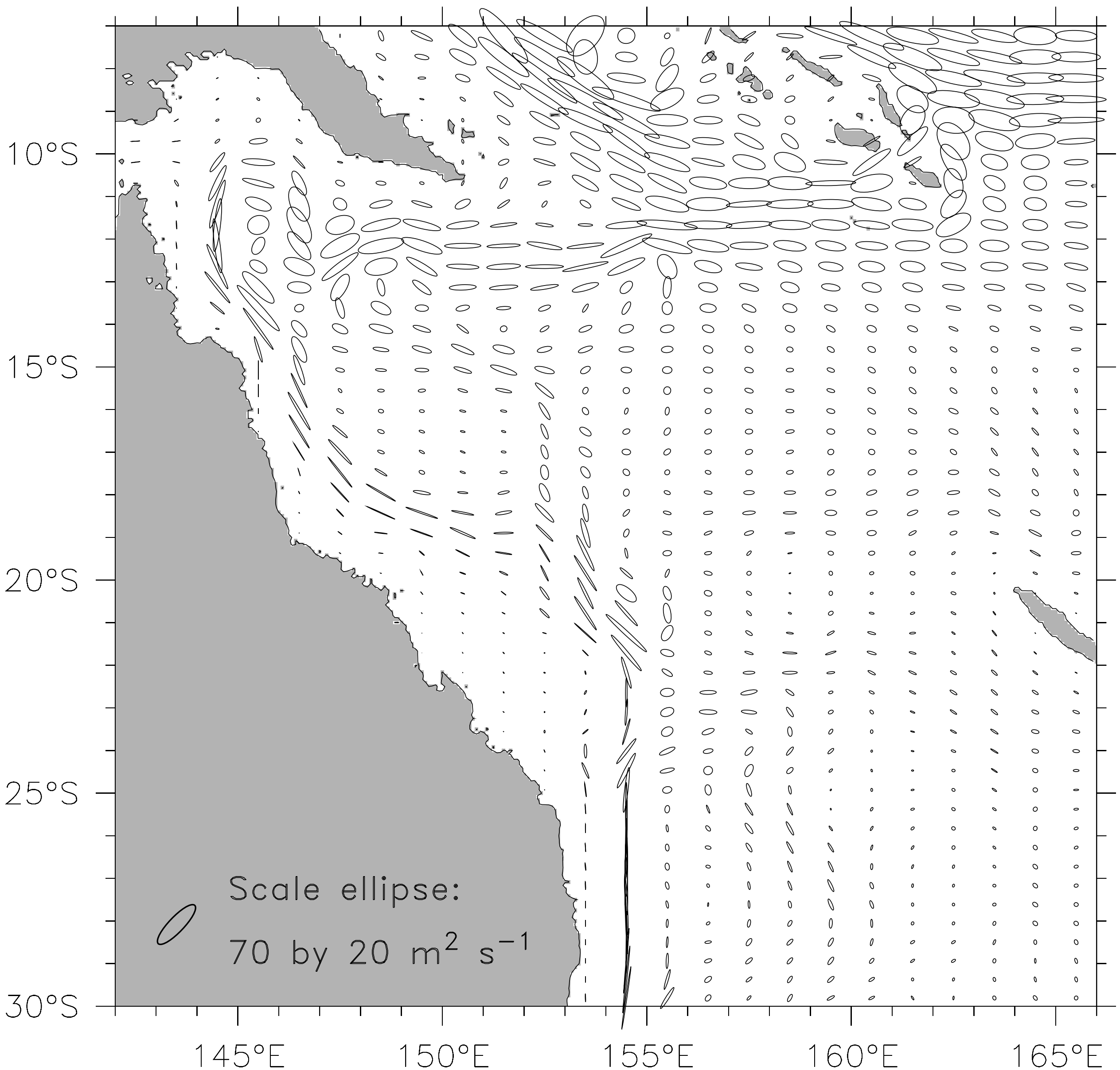


Red dots show monthly anomalies

At this location, 98% of the variance is expressed along the major axis.

(Units $m^2\ s^{-1}$)

Annual cycle transport variance ellipses



0-2060m transport

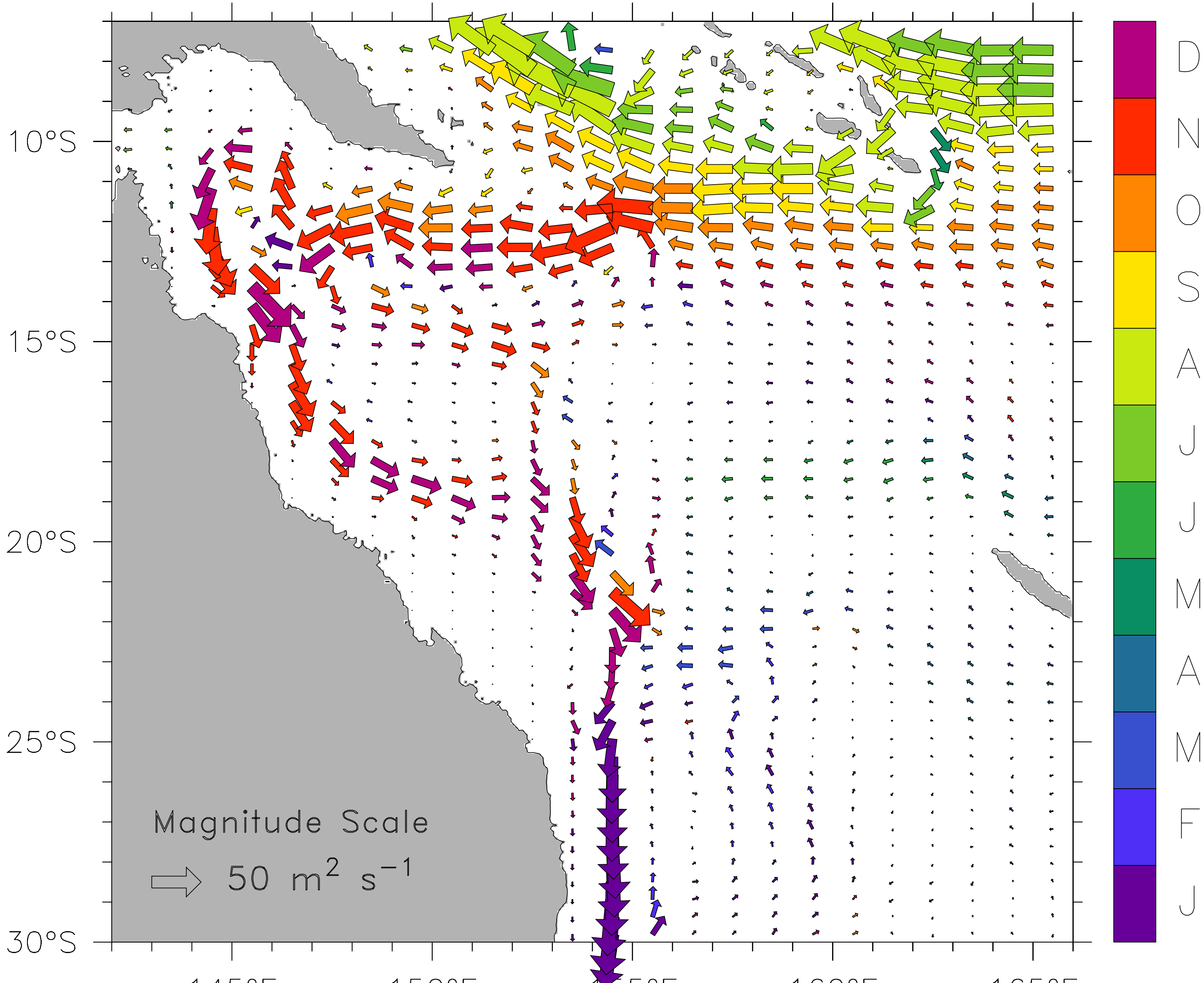
Small variability in the interior gyre.

Large-amplitude currents in the tropics and along the western boundary.

Elongated ellipses show 80-90+% of variance on the major axes, which are mostly aligned along the mean currents.

➡ Use the major axes to define a current-following coordinate.

1 cpy transport harmonic from variance ellipses



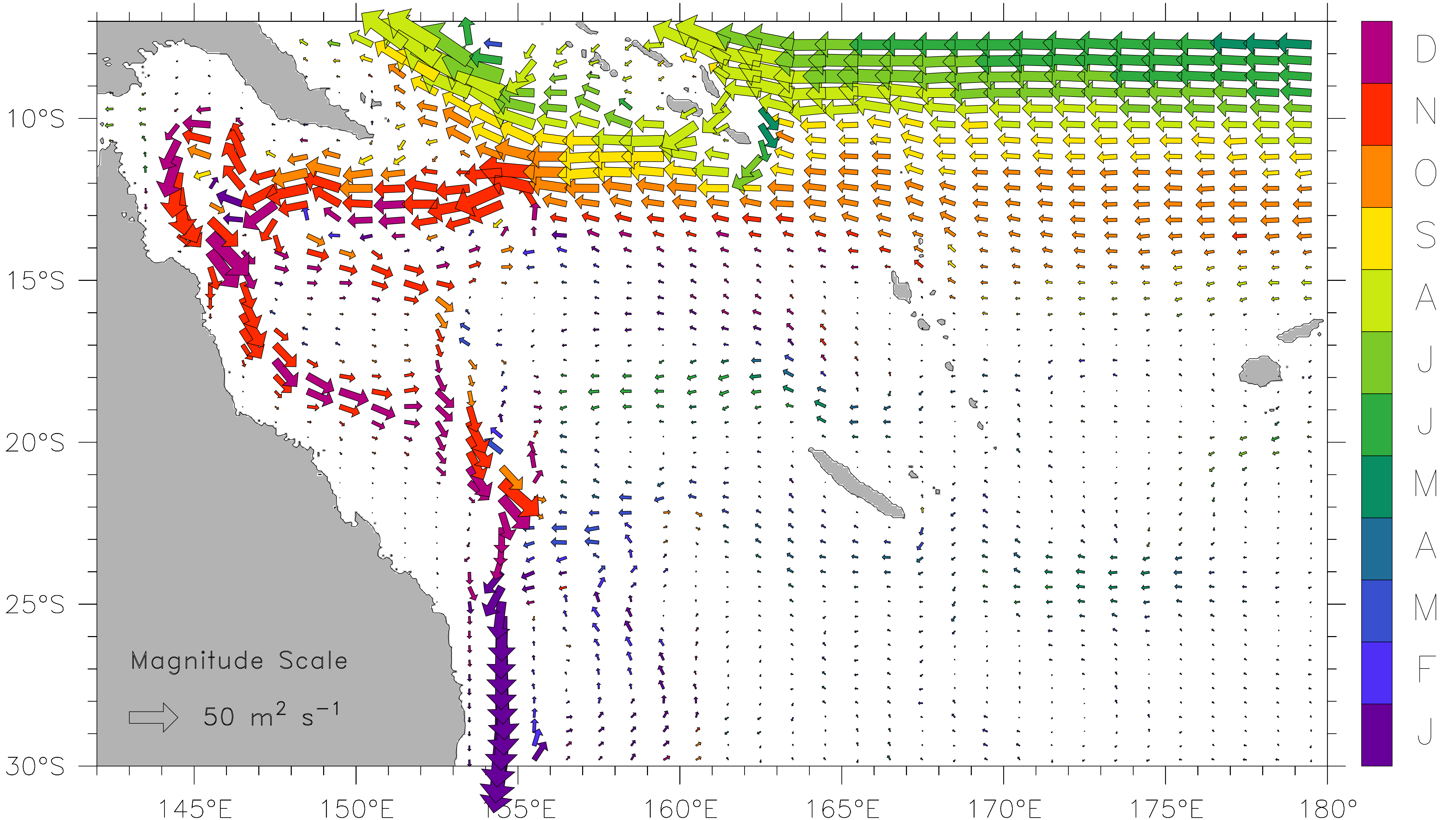
Vector size = amplitude (scale lower left)

Direction = major axis of variance ellipse (not mean current)

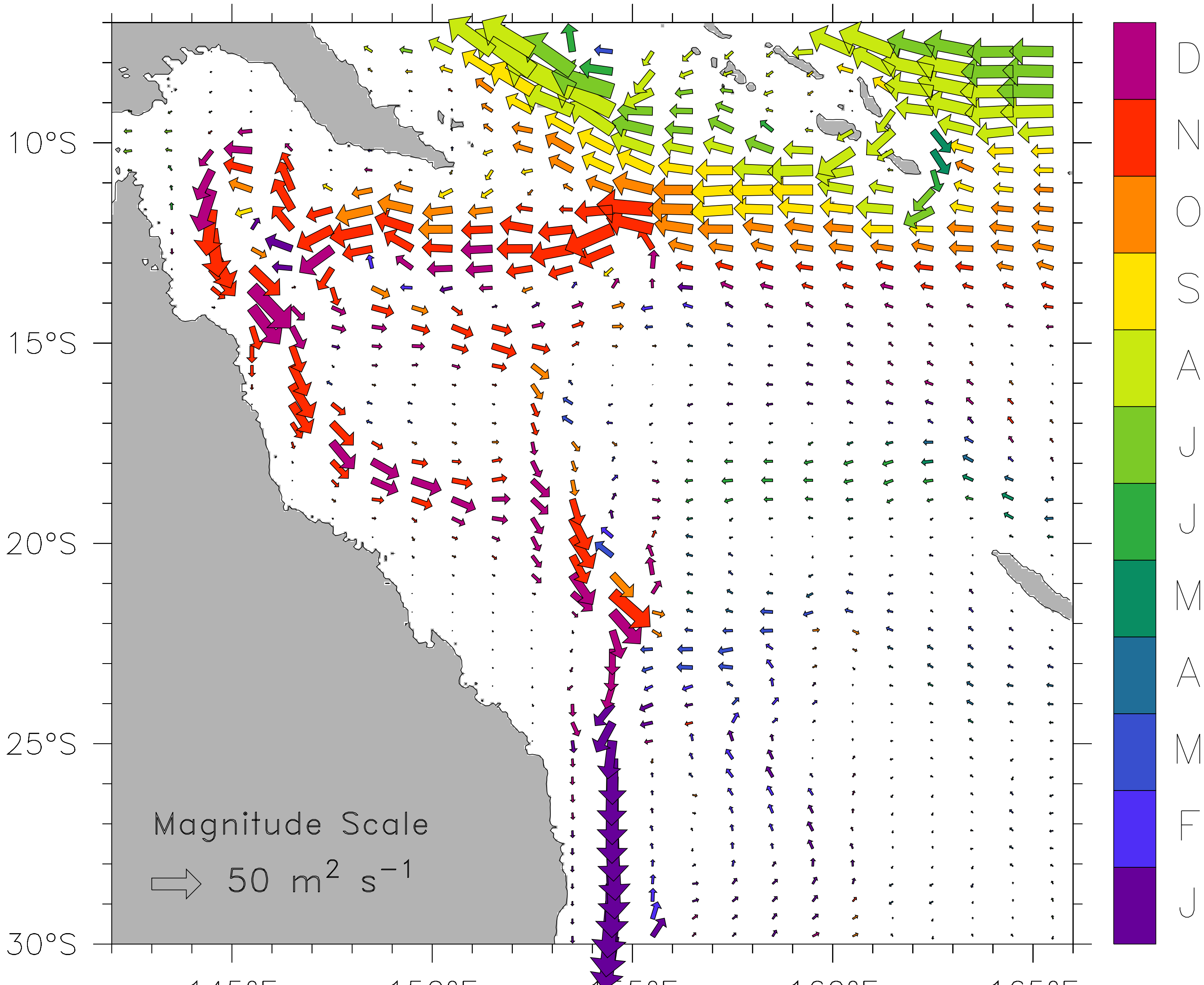
Color = month of maximum transport

The same pattern extends to the east

Little transport variance in the gyre center

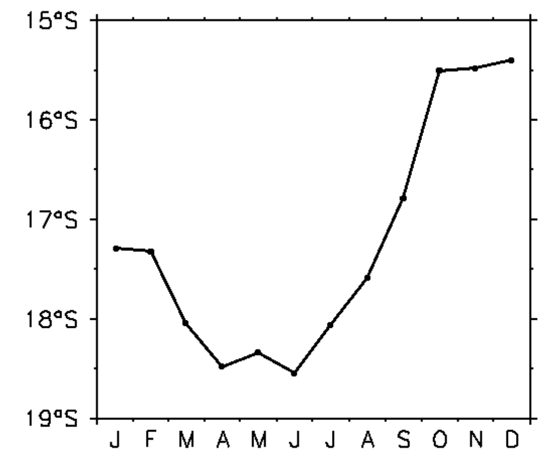


Do subtropical WBC anomalies connect to the equator?



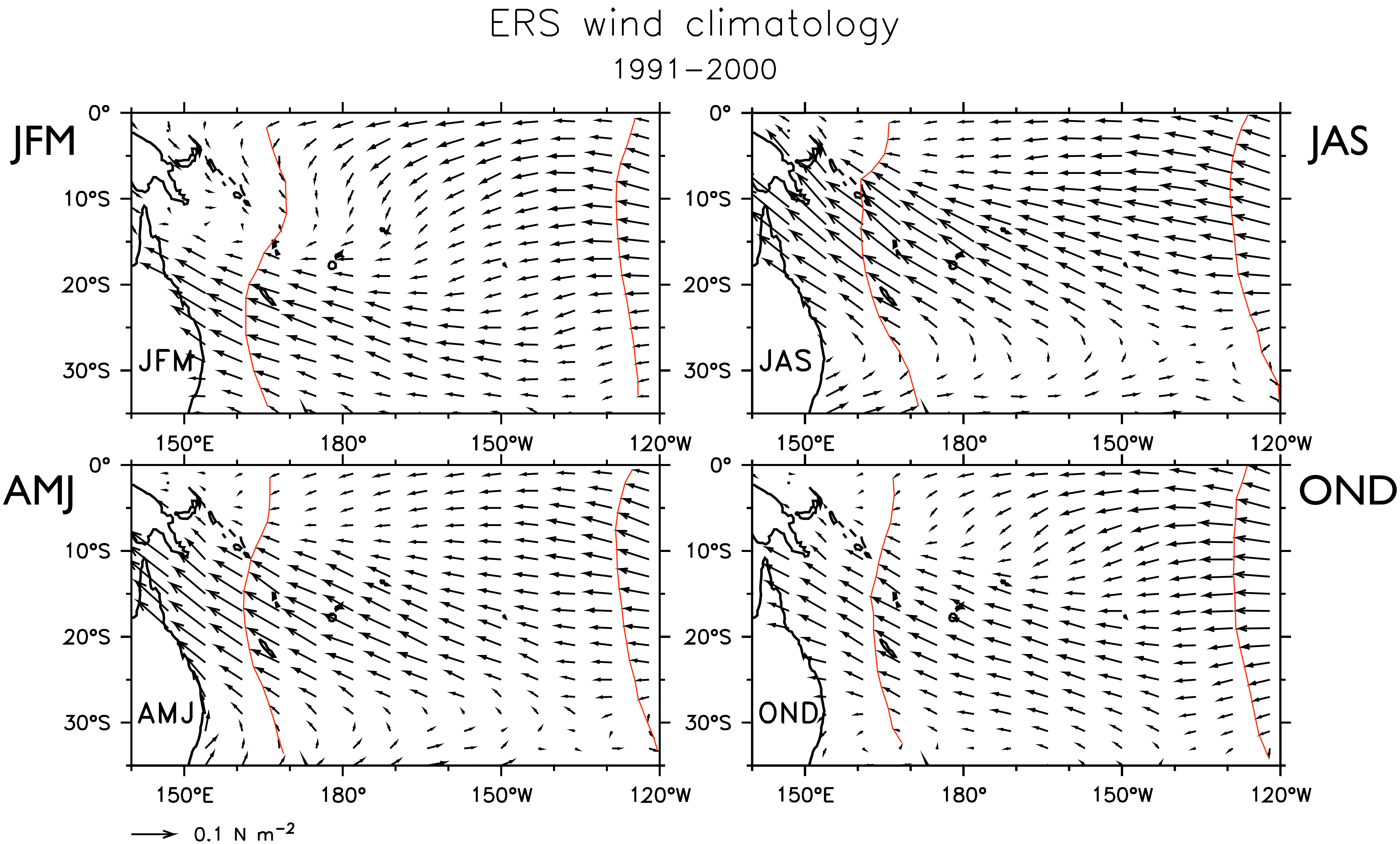
The WBC along the entire coast of Australia fluctuates coherently, while anomalies of the NGCC are nearly of the opposite phase.

Bifurcation latitude



Annual coastal Australia WBC anomalies do not represent corresponding transports to the equator.

Curl variations are much larger in the west



The familiar reduced-gravity long Rossby wave model

$$\frac{\partial h}{\partial t} + c_r \frac{\partial h}{\partial x} + Rh = -Curl\left(\frac{\tau}{f\rho}\right), \qquad c_r = -\beta \frac{c^2}{f^2}$$

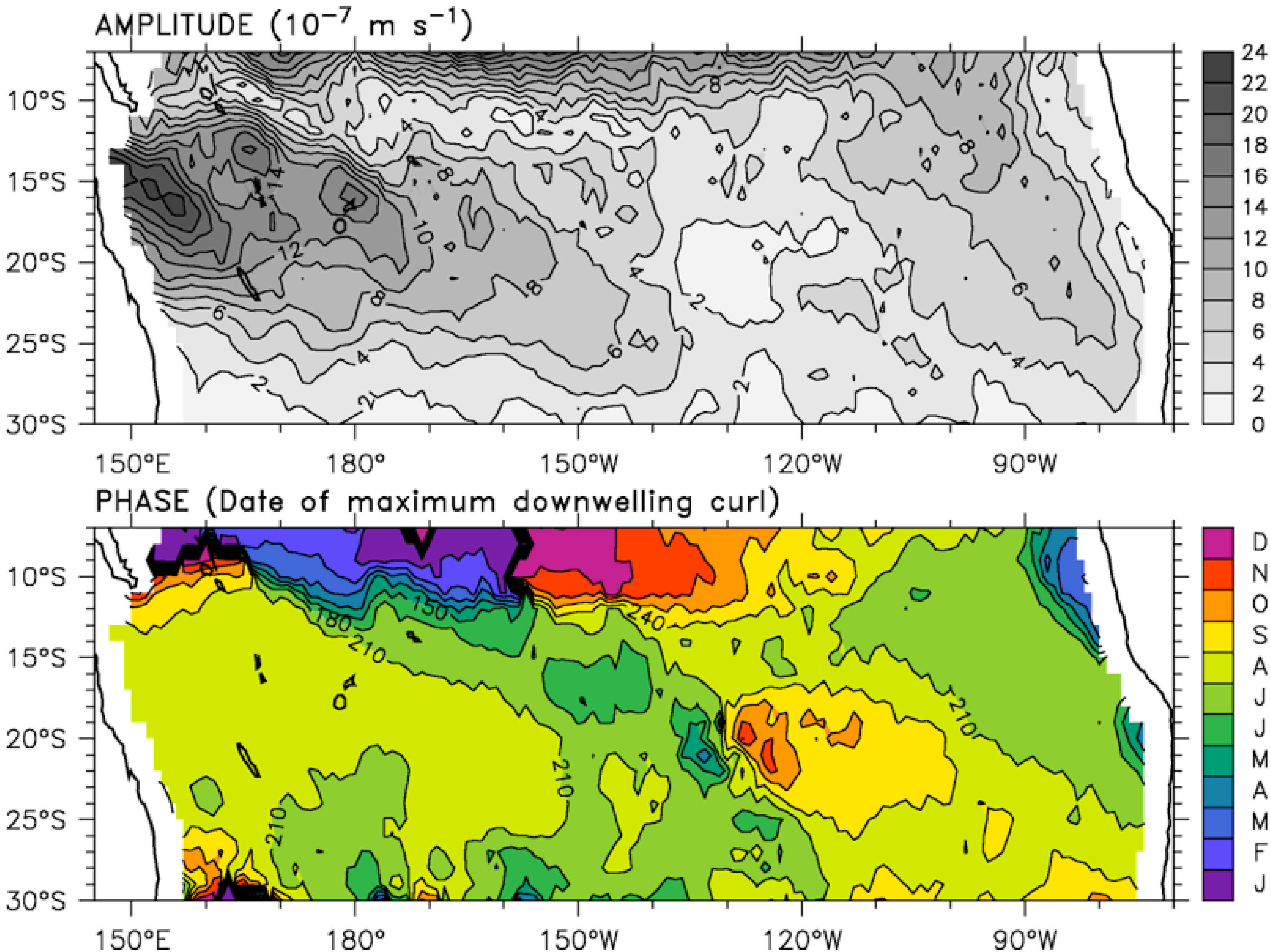
h is the ULT anomaly, c is the Kelvin speed, R is a damping timescale, (2 yr)$^{-1}$.

The solution is found at each latitude independently:

$$h(x,t) = -\frac{1}{c_r}\int_{x_E}^{x} e^{-\frac{R}{c_r}(x-x')} Curl\left(\frac{\tau(x', t - \frac{x-x'}{c_r})}{f\rho}\right) dx'$$

The model is forced with an annual cycle of ERS winds (1991-2000), assuming no eastern boundary influence.

1 cpy harmonic of $Curl(\tau/f\rho)$



Equatorial-subtropical divide along 11°S

ERS winds 1991-2000

Because the winds have a simple form ....

Chen and Qiu (2004) showed that for winds of the form: (a standing oscillation with uniform phase, decaying eastward)

$$Curl\left(\frac{\tau}{\rho f}\right) = Be^{i\omega t}e^{-(x-x_w)/L}$$

The Rossby solution is also a standing oscillation:

$$h(x,t) = \left(\frac{1}{i\omega - \frac{c_r}{L}}\right) Curl\left(\frac{\tau}{\rho f}\right)$$

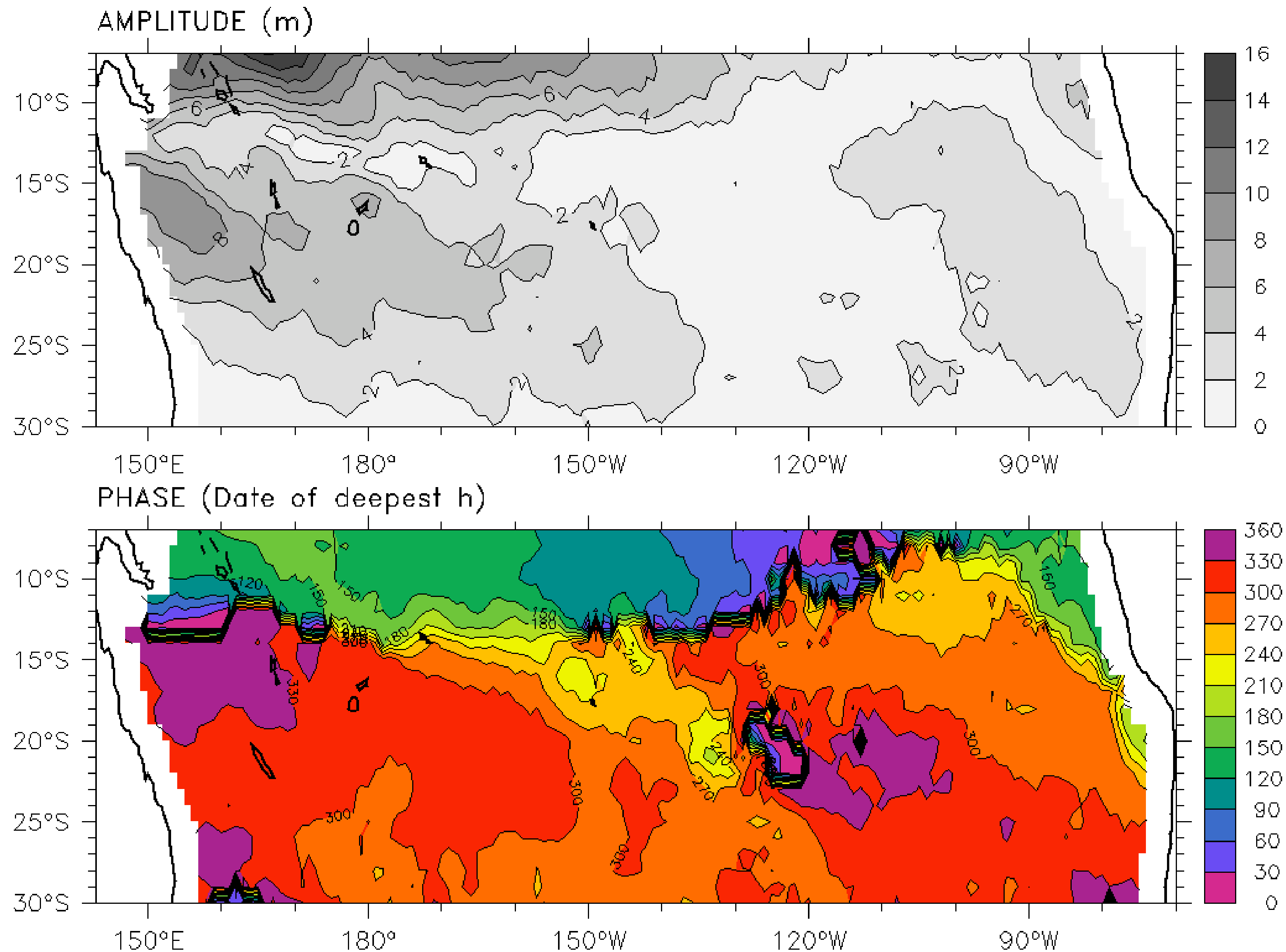
which lags the Curl by $tan^{-1}(\omega L/c_r)$ = 2.5-3 months:

$$= -\underbrace{\left(1 + i\frac{\omega L}{c_r}\right)}_{\text{Phase lag}}\underbrace{\left(\frac{1}{\frac{\omega^2 L}{c_r} + \frac{c_r}{L}}\right)}_{\text{Amplitude}} Curl\left(\frac{\tau}{\rho f}\right)$$

- Propagating Rossby waves will not be apparent in this solution (will look a lot like Ekman pumping)
- Expect uniform phase (max h in Nov) and growing amplitude in the west

Rossby solution h implied by Chen/Qiu 04 form of wind forcing

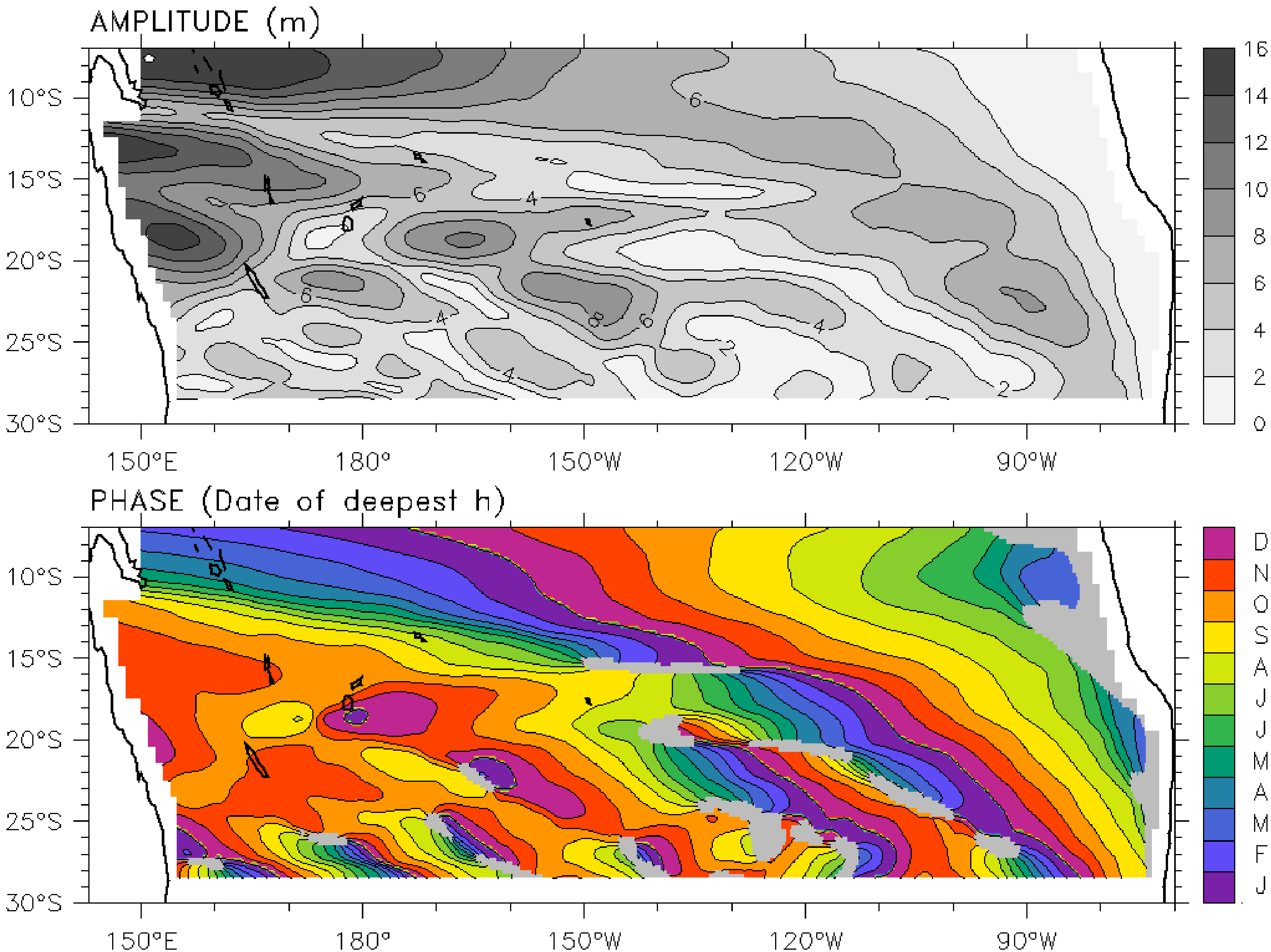
$h = \mathrm{Curl}(\tau/f\rho)/(i\omega - c_r/L)$. ERS winds 1 cpy. $c_k = 3.5\ \mathrm{m\ s^{-1}}$, $L = 9000\mathrm{km}$



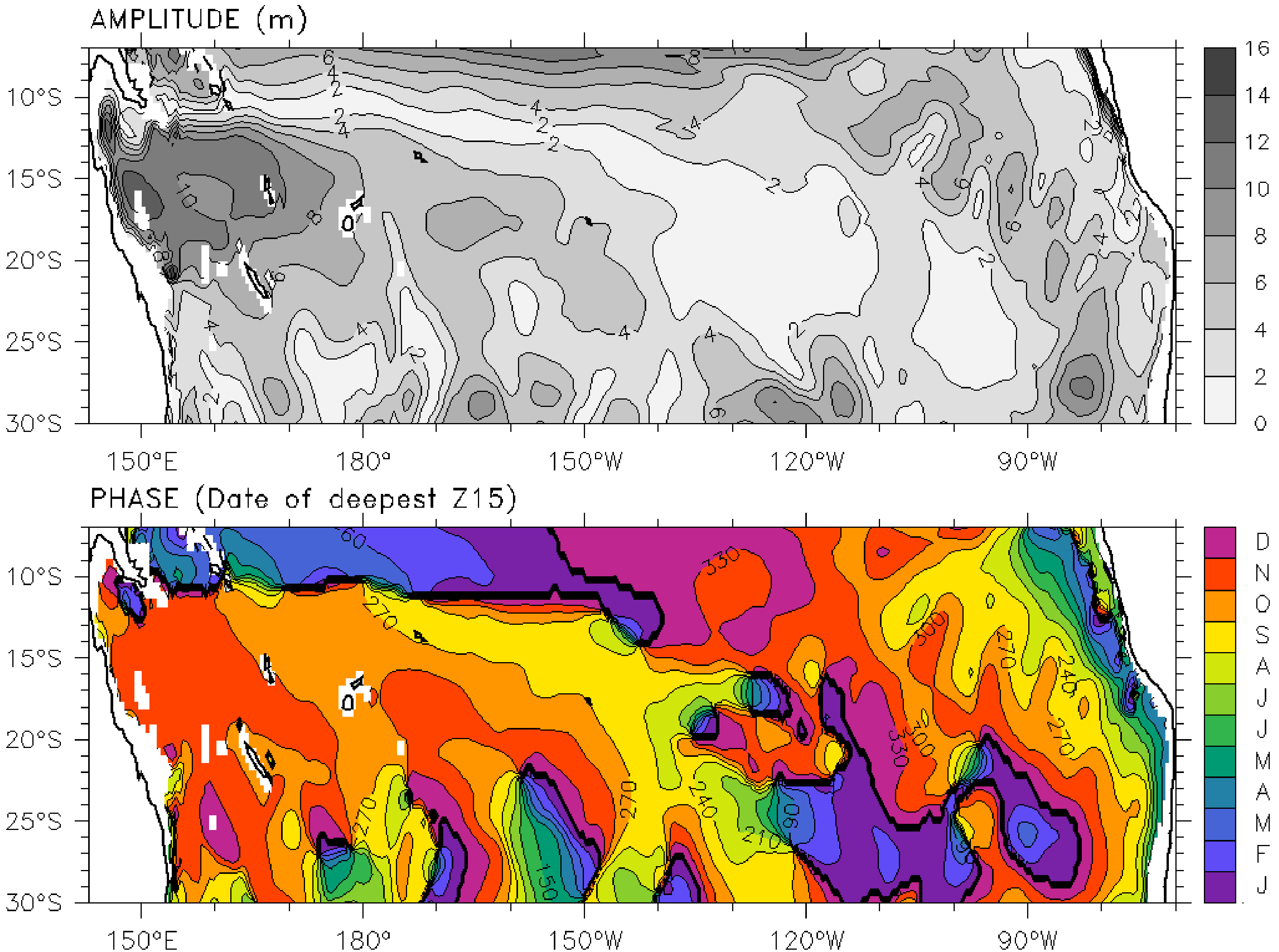
$\alpha = \omega L/c_r$. $\quad 1/(i\omega - c_r/L) = -(1+i\alpha)/(\omega(\alpha + 1/\alpha))$

$\mathrm{Lag} = \tan^{-1}(\alpha)$. Magnitude $= \mathrm{Curl}(\tau/f\rho)[(1+\alpha)^{1/2}/\omega(\alpha+1/\alpha)]$

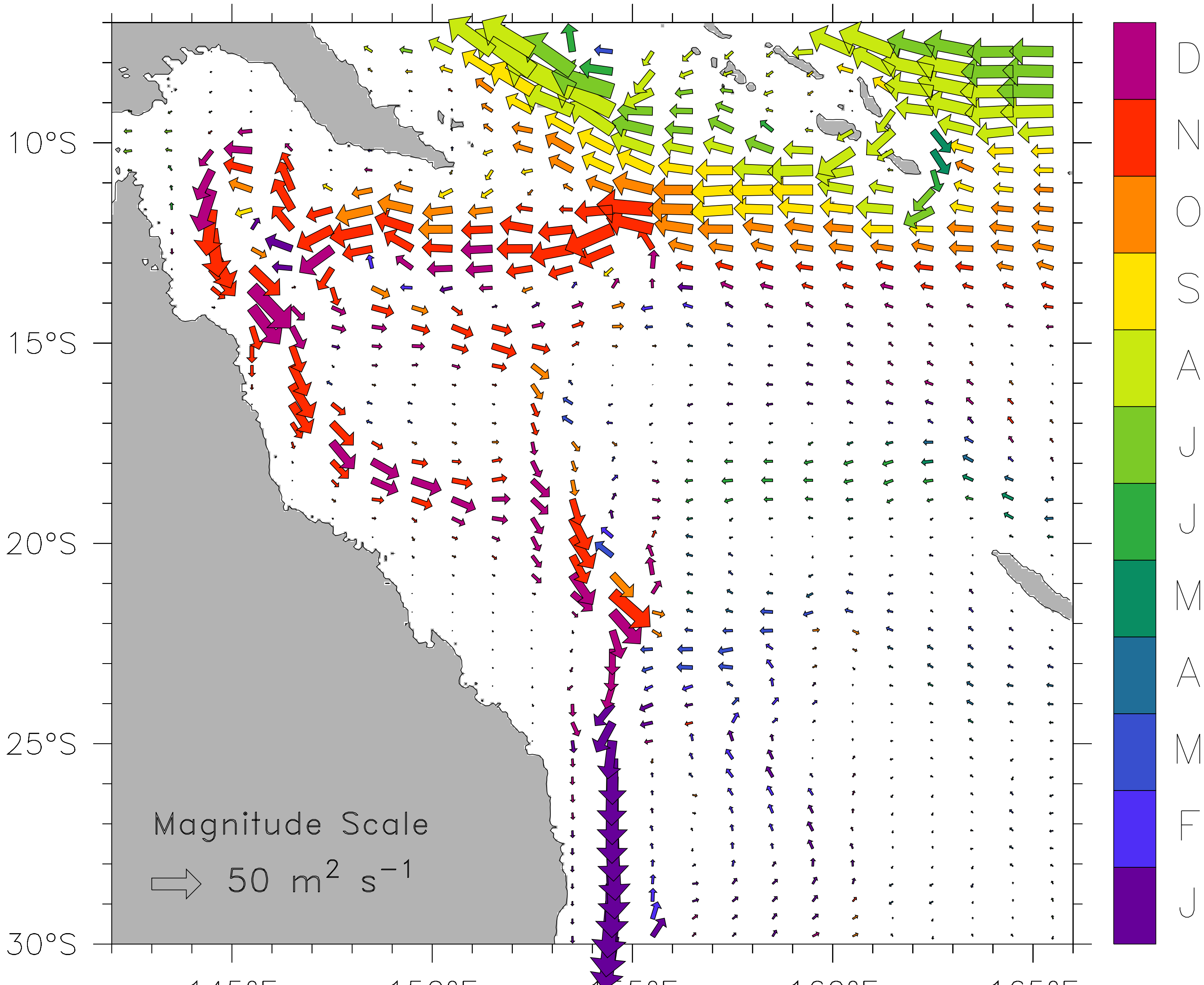
1 cpy harmonic of Rossby model h (real winds)



1 cpy harmonic of OGCM 15°C depth



The annual cycle is a spinup and spindown of the gyre



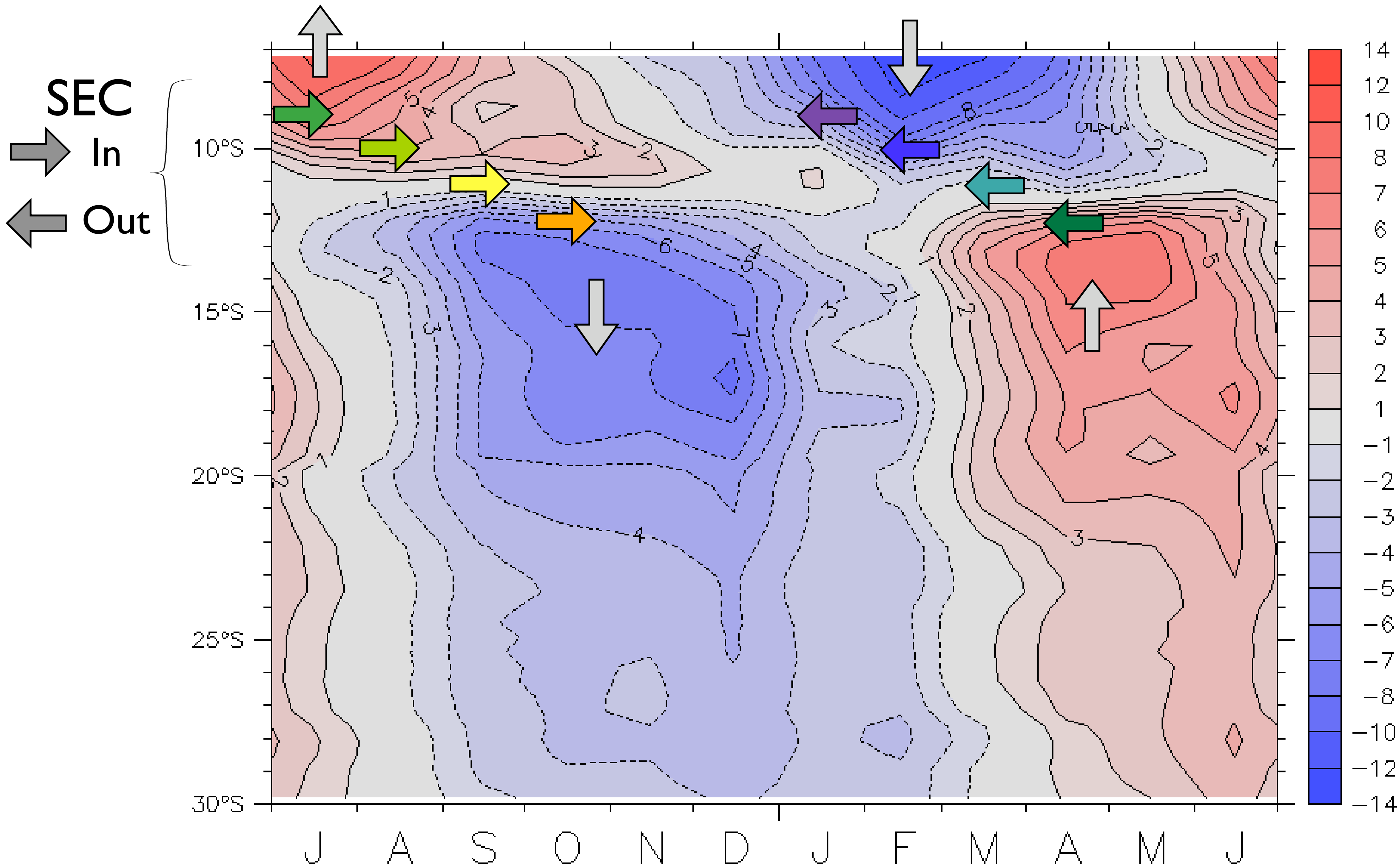
The wind-driven changes are a shoaling of the gyre in the 1st half of the year, and a deepening in the 2nd.

The resulting transport anomalies are alternately clockwise (spindown) and anticlockwise, but the tropical side is much stronger.

The OGCM solution shows that this also describes the western boundary changes.

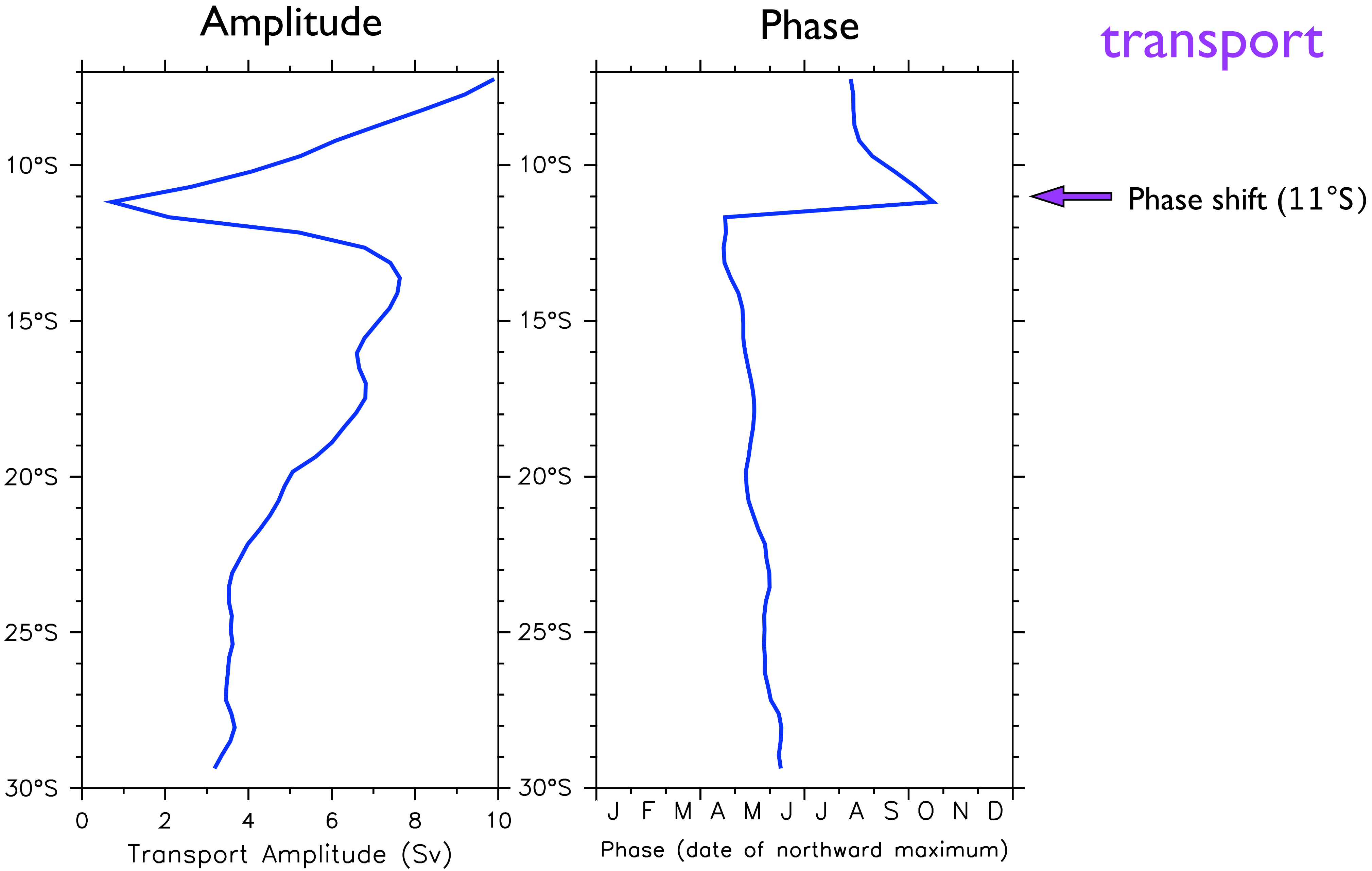
Western boundary transport (Sv)

In relation to SEC inflow



ORCA model

1 cpy harmonic of WBC transport



Deducing western boundary current anomalies from the interior Rossby solution

- By its neglect of velocity acceleration terms, the long Rossby model explicitly excludes western boundary dynamics.
- However, an evaluation can be made by assuming that pressure at the coast of Australia remains constant (on seasonal timescales), while the Rossby model gives the pressure just offshore.

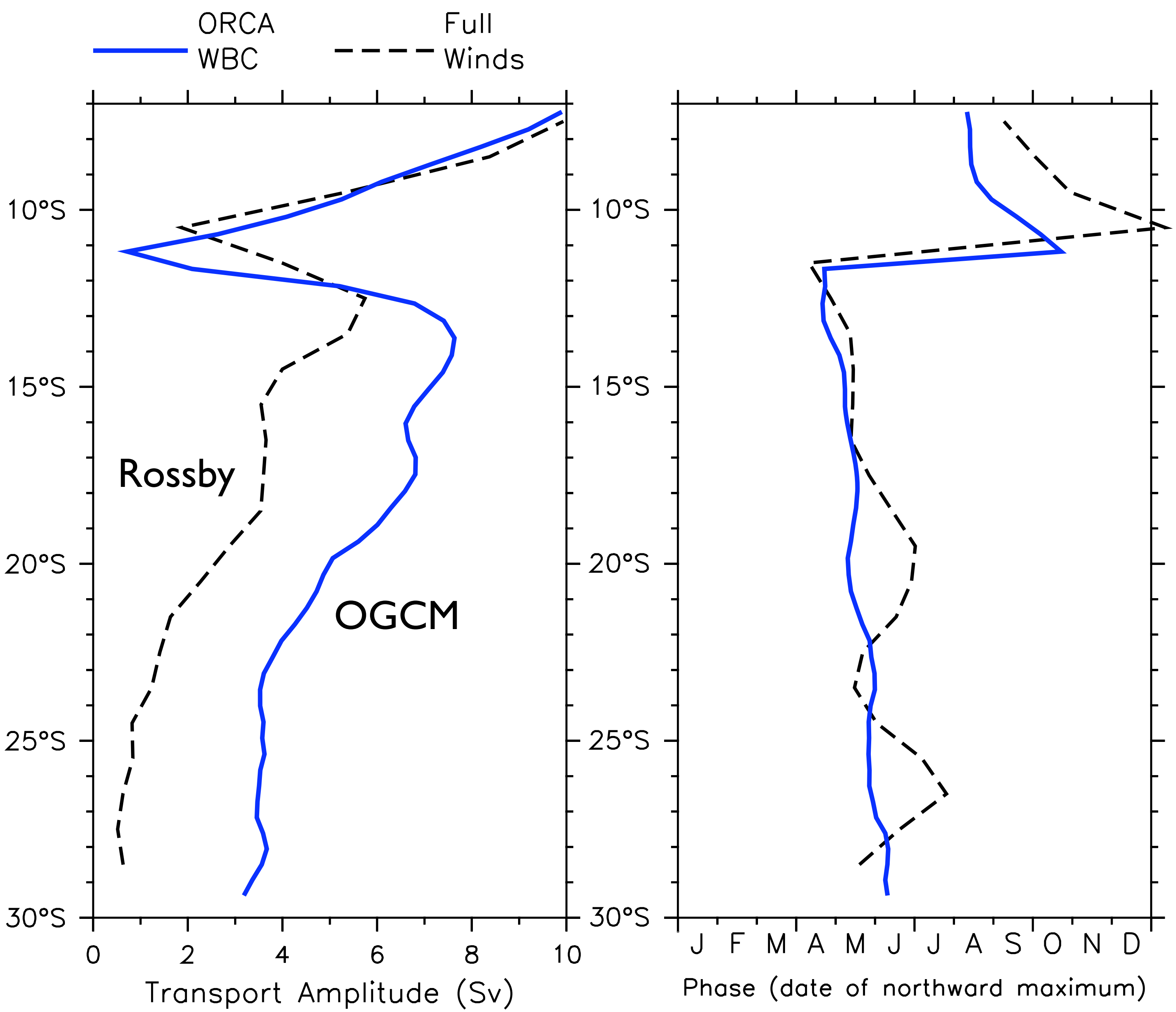
In the reduced gravity system, the WBC transport anomaly is:

$$V = \int_{x_{W-}}^{x_W} H v_g dx = \int_{x_{W-}}^{x_W} H \frac{g'}{f} \frac{\partial h}{\partial x} dx = \frac{c^2}{f} \Delta h$$

- With the assumption of constant pressure at the coast, Δh is just the westernmost Rossby pycnocline anomaly.
- Since the Rossby model is linear, can isolate elements of the wind.

Compare Rossby model ($V=h_{RW}c^2/f$)

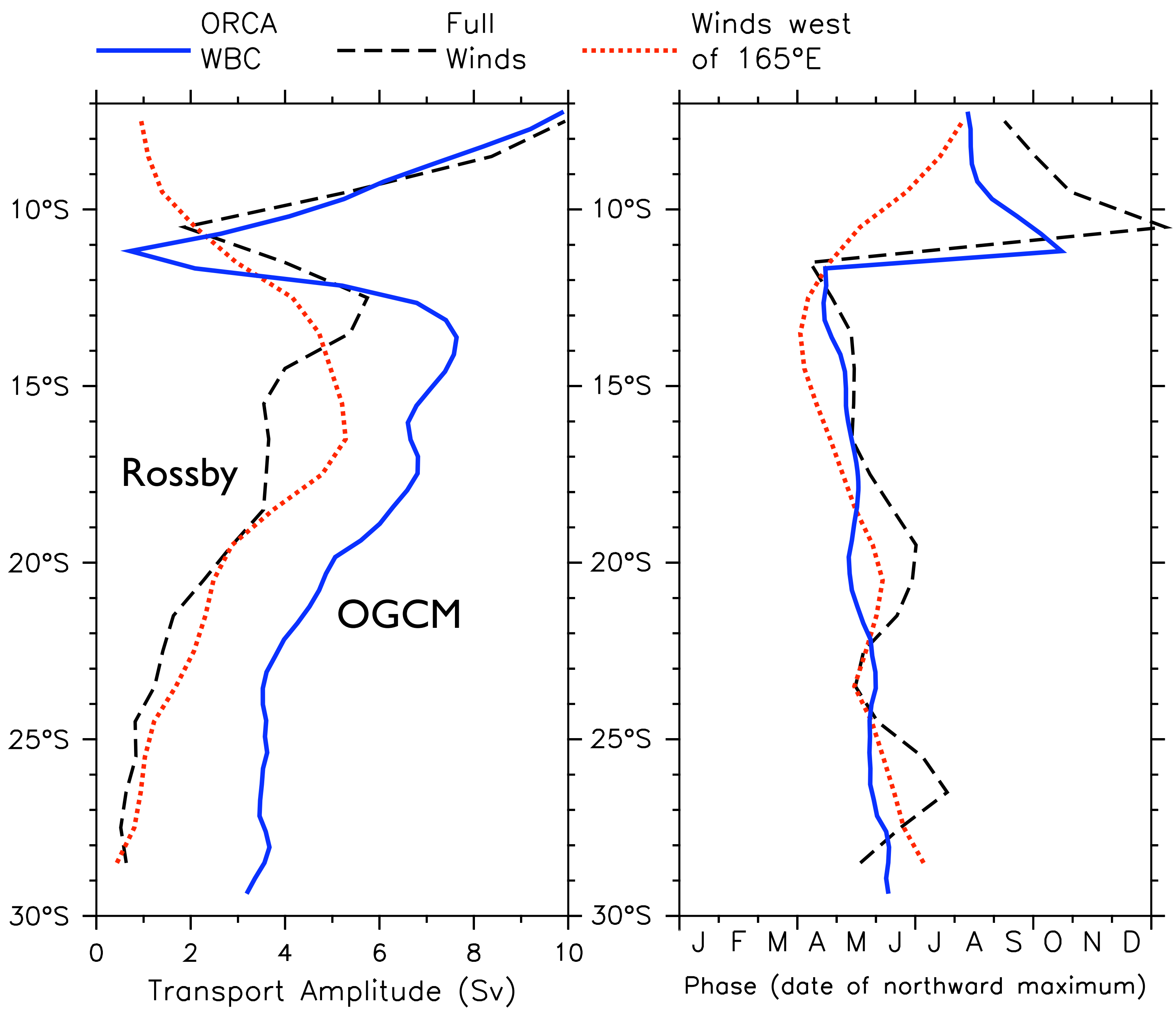
1 cpy harmonic of WBC transport



The 11°S phase shift is found in the Rossby solution, though it excludes western boundary dynamics and "knows" nothing about the continent.

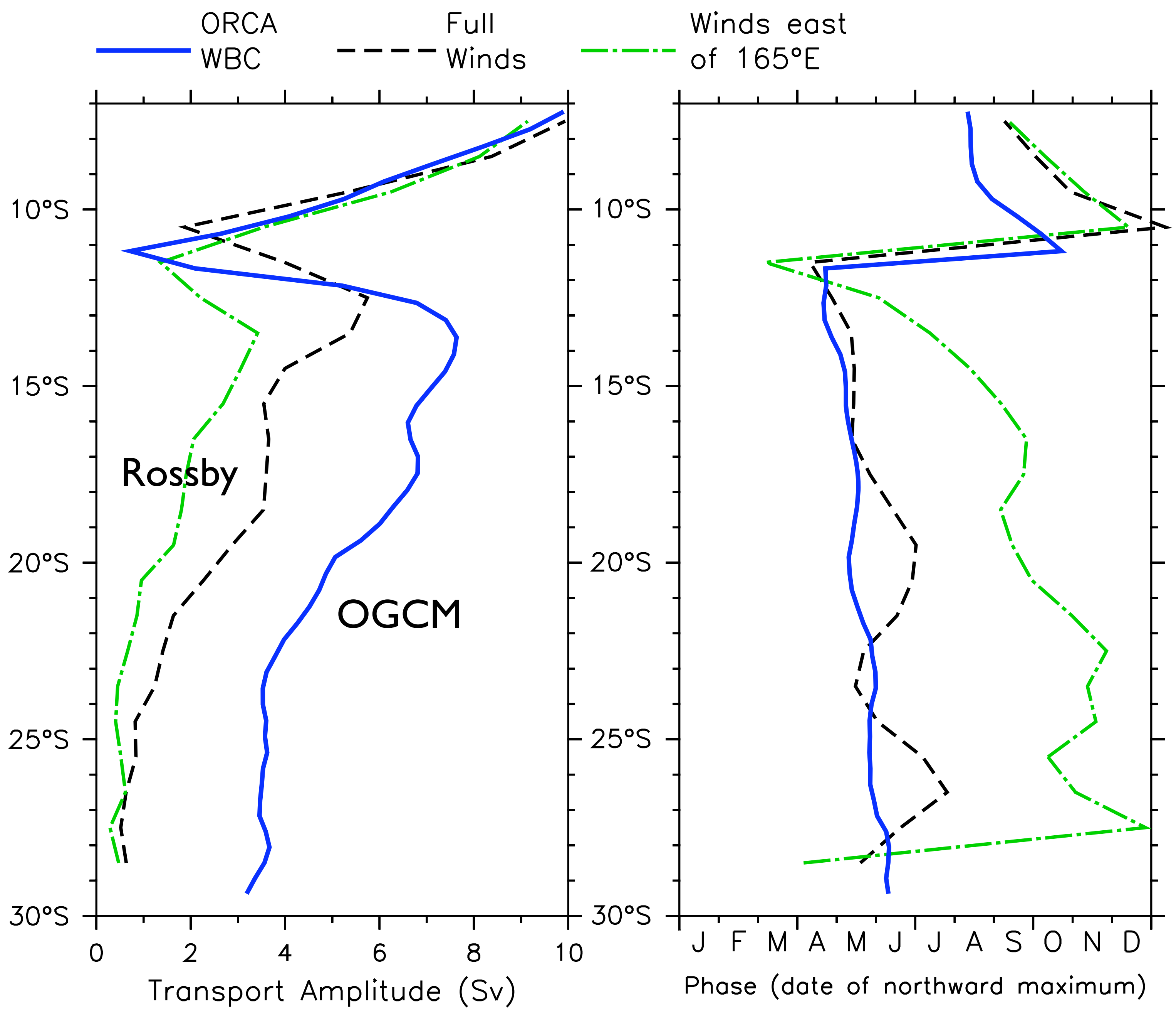
1 cpy harmonic of WBC transport

Compare Rossby model ($V=h_{RW}c^2/f$)



South of the 11°S phase shift, the Rossby solution forced only by winds west of 165°E is nearly identical to the full solution.

Compare Rossby model ($V=h_{RW}c^2/f$)



1 cpy harmonic of WBC transport

South of the 11°S phase shift, the Rossby solution forced only by winds east of 165°E is very different from the full solution.

But it matches the full solution north of 11°S.

Conclude:

- A linear Rossby model represents much of the annual variability in the subtropical South Pacific. The interior of the gyre heaves in a standing oscillation, driven by strong wind variations in the west.
- WBCs along the entire east coast of Australia fluctuate coherently. The linear model is also useful for interpreting WBC variability.
- The out of phase WBC across 10°S is due to interior winds, not to boundary dynamics or the shape of the coast.
- The bifurcation latitude is meaningless with respect to annual transport from the South Pacific subtropical gyre to the equator. What about the North Pacific?
- The OGCM predicts the occurrence of annual WBCs on the deep east flanks of the Queensland Plateau and the Solomon Islands.